

The sensitivity of cosmic ray air shower experiments for excited lepton detection

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Abstract

In models with substructure in the fermionic sector, excited fermion states are expected. Excited leptons could be produced in the interaction of high energy quasi-horizontal cosmic neutrinos with the atmosphere via neutral and charged current processes, $\nu N \rightarrow \nu^* X$ and $\nu N \rightarrow \ell^* X$. The hadronic component X, and possibly part of the excited lepton decay products, would originate an extensive air shower, observable in large cosmic ray experiments. In this paper, the sensitivity of present and planned very high energy cosmic ray experiments to excited lepton production is estimated and discussed.

Key words: compositeness, excited leptons, UHECR, EAS, neutrinos, AGASA, Fly's Eye, Auger, EUSO, OWL

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1 Introduction

Compositeness is a never discarded hypothesis for explaining the complexity of the present fundamental particle picture. In models with substructure in the fermionic sector, excited fermion states are expected. In the past years many searches were performed in the accelerators around the world [1]. So far, no evidence for excited fermions was found, and stringent limits were set at the electroweak scale.

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The race for higher energies has new partners in present and future large cosmic rays experiments. These experiments, covering huge detection areas, are able to explore the high energy tail of the cosmic ray spectrum, reaching centre-of-mass energies orders of magnitude above those of man made accelerators. Although having poorer detection capabilities and large uncertainties on the beam composition and fluxes, cosmic ray experiments present a unique opportunity to look for new physics at scales far beyond the TeV.

Energetic cosmic particles interact with the atmosphere of Earth originating Extensive Air Showers (EAS) containing billions of particles. While cosmic particles with strong or electromagnetic charges are absorbed in the first layers of the atmosphere, neutrinos have a much lower interaction cross-section and can easily travel large distances. Energetic cosmic neutrinos, although not yet observed and with very large uncertainties on the expected fluxes, are predicted on rather solid grounds [2]. Nearly horizontal neutrinos, seeing a large target volume and with negligible background from “ordinary” cosmic rays, are thus an ideal beam to explore possible rare processes [3].

In this paper, the possibility of excited lepton searches in current (AGASA [4], Fly’s Eye [5]) and future (Auger [6], EUSO [7], OWL [8]) very high energy cosmic ray experiments is discussed. Excited leptons could be produced in the interaction of high energy quasi-horizontal cosmic neutrinos with the atmosphere via neutral and charged current processes, $\nu N \rightarrow \nu^* X$ and $\nu N \rightarrow \ell^* X$ (ν^* and ℓ^* representing neutral and charged excited leptons, respectively). The hadronic component X , and possibly part of the excited lepton decay products, would originate an extensive air shower, observable by large cosmic ray experiments. As the initial beam must contain all three neutrino flavours, one expects the production of excited leptons of first, second and third family. In the specific case of the third family excited leptons decaying into τX , the subsequent decay of the tau lepton may originate a second visible air shower within the acceptance of the experiment and thus giving rise to a double bang event topology [15,16]. Excited leptons are hypothetical particles, and their unknown interactions are often described at the electroweak scale by effective models. In this work the well known model of [9] is assumed. This model is described in section 2, where the excited lepton production cross-sections are obtained and the decay branching ratios at the relevant energies and masses are discussed. In section 3 the expected sensitivity to excited lepton events of the largest available and planned cosmic ray experiments is estimated and discussed. Some conclusions are finally drawn.

2 Production and decay of excited leptons

The $SU(2) \times U(1)$ gauge invariant effective Lagrangian describing the magnetic transition between excited leptons and the Standard Model (SM) leptons has the form [9]:

$$\mathcal{L}_{l^*} = \frac{1}{2\Lambda} \overline{L^*} \sigma^{\mu\nu} \left[g f \frac{\boldsymbol{\tau}}{2} \mathbf{W}_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] L_L + \text{h.c.} \quad (1)$$

where $L^* = L_L^* + L_R^*$, with:

$$L_L^* = \begin{bmatrix} \nu^* \\ \ell^* \end{bmatrix}_L; \quad L_R^* = \begin{bmatrix} \nu^* \\ \ell^* \end{bmatrix}_R$$

and L_L is the weak isodoublet with the left-handed components of the SM leptons. Above, $\sigma^{\mu\nu}$ is the covariant bilinear tensor, $\boldsymbol{\tau}$ are the Pauli matrices, Y is the weak hypercharge, $\mathbf{W}_{\mu\nu}$ and $B_{\mu\nu}$ represent the gauge field tensors of $SU(2)$ and $U(1)$, respectively, and g and g' are the corresponding SM coupling constants. The parameter Λ sets the compositeness scale and f, f' are weight factors associated with the two gauge groups.

This Lagrangian describes the ll^*V vertex, and thus the single production of excited leptons and their decays. The strength of the ll^*V coupling is parameterised through f and f' . Form factors and anomalous magnetic moments of the excited leptons were not considered. From this Lagrangian we can derive the vertex

$$\Gamma_\mu^{Vl^*l} = \frac{e}{2\Lambda} q^\nu \sigma_{\mu\nu} (1 - \gamma_5) f_V$$

where the couplings to the physical gauge bosons are

$$f_\gamma = e_l f' + I_{3L}(f - f'), \quad f_W = \frac{1}{\sqrt{2}s_W} f, \quad f_Z = \frac{I_{3L}(c_W^2 f + s_W^2 f') - e_l s_W^2 f'}{s_W c_W}$$

I_{3L} being the fermion weak isospin and $s_W = \sin \theta_W, c_W = \cos \theta_W$, with θ_W the SM weak mixing angle. To reduce the number of free parameters, it is customary to assume a relation between f and f' . In this paper, the scenarios $f = f'$ and $f = -f'$ will be considered. In these cases, the single excited lepton production cross-section depends only on the ratio $|f|/\Lambda$ and on the excited lepton mass. It is worth noting that for $f = f'$ the coupling of the excited neutrinos to the photon vanishes. The same is true for excited charged leptons if $f = -f'$.

2.1 Production

The production of excited leptons in neutrino-parton collisions is described at the lowest order by the t -channel exchange of a W^\pm boson, in the case of excited charged lepton production (Charged Current, CC), or of a Z^0 boson, for excited neutrino production (Neutral Current, NC). In the case of the neutral currents, an additional contribution from t -channel γ exchange arises in scenarios with $f \neq f'$, due to the non-vanishing coupling to the photon. The tree level diagrams are shown in Fig.1.

From the above Lagrangian, the differential cross-section for neutrino-parton interactions can be written as:

$$\frac{d\sigma_{\nu q}}{dQ^2}(\hat{s}, Q^2) = 2\pi\alpha^2 \left(\frac{f}{\Lambda}\right)^2 Q^2 [D_l(Q^2)S(\hat{s}, Q^2) \pm \bar{D}_l(Q^2)A(\hat{s}, Q^2)] \quad (2)$$

where the plus and minus sign apply for partons and antipartons, respectively, $-Q^2$ is the momentum transfer, \hat{s} is the parton level centre-of-mass energy and:

$$S(\hat{s}, Q^2) = 2 - (2 - r) \left(\frac{Q^2}{\hat{s}} + r \right), \quad A(\hat{s}, Q^2) = r \left(2 - \frac{Q^2}{\hat{s}} - r \right)$$

where $r \equiv m_*^2/\hat{s}$ and m_*^2 is the excited lepton mass. In the case of charged excited lepton production via CC, the D_l , \bar{D}_l functions can be written as:

$$D_e = \bar{D}_e = \left(\frac{f_W}{f} \right)^2 \frac{a_W^2 + v_W^2}{(Q^2 + M_W^2)^2}.$$

For excited neutrino production via NC, both the Z^0 and the γ contribution have to be taken into account and the D_l , \bar{D}_l can be written:

$$D_\nu = \frac{e_q^2}{(Q^2)^2} \left(\frac{f_\gamma}{f} \right)^2 + \frac{2e_q v_q^Z}{Q^2(Q^2 + M_Z^2)} \left(\frac{f_\gamma f_Z}{f} \right)^2 + \frac{[(v_q^Z)^2 + (a_q^Z)^2]}{(Q^2 + M_Z^2)^2} \left(\frac{f_Z}{f} \right)^2$$

$$\bar{D}_\nu = \frac{2e_q a_q^Z}{Q^2(Q^2 + M_Z^2)} \left(\frac{f_\gamma f_Z}{f} \right)^2 + \frac{2v_q^Z a_q^Z}{(Q^2 + M_Z^2)^2} \left(\frac{f_Z}{f} \right)^2.$$

In the expressions above, the SM couplings are:

$$a_W = v_W = \frac{1}{2\sqrt{2}s_W}, \quad v_q^Z = \frac{2I_{3L}^q - 4e_q s_W^2}{4c_W s_W}, \quad a_q^Z = \frac{2I_{3L}^q}{4c_W s_W}$$

where I_{3L}^q is the quark weak isospin.

The double differential Deep Inelastic Scattering (DIS) neutrino-nucleon cross-sections can be written as

$$\begin{aligned}
\frac{d^2\sigma_{\nu N}}{dx dy} &= \sum_q q(x, Q^2) \frac{d\sigma_{\nu q}}{dy} \Big|_{\hat{s}=xs} = \sum_q q(x, Q^2) xs \frac{d\sigma_{\nu q}}{dQ^2} \Big|_{\hat{s}=xs} = \\
&= 2\pi\alpha^2 \left(\frac{f}{\Lambda}\right)^2 (xs)^2 y \sum_q [D_l(Q^2)S(x, y) \pm \bar{D}_l(Q^2)A(x, y)] q(x, Q^2) \quad (3)
\end{aligned}$$

where $y = (E_\nu - E^*)/E_\nu$ is the inelasticity parameter (E_ν is the incident neutrino energy and E^* is the excited lepton energy), $x = Q^2/sy$ is the Bjorken variable, $q(x, Q^2)$ are the quark distribution functions and the sum runs over the quark types. We neglect the top distribution function, but we take into account the threshold suppression of the $b \rightarrow t$ transition, using the standard “slow-rescaling” prescription [10]. In this work the CTEQ6-DIS parton distribution functions [11] were used.

The total CC or NC production cross-sections will thus be given by:

$$\sigma_{\nu N}(eN \rightarrow l^*X) = \int_{(m_*^2 + Q_0^2)/s}^1 dx \int_{Q_0^2/xs}^{1-x} dy \frac{d^2\sigma_{\nu N}}{dx dy} + \sigma_{el} + \sigma_{low} \quad (4)$$

where the first term is the deep inelastic scattering (DIS) contribution, and σ_{el} and σ_{low} are the elastic and low inelastic contributions, respectively. These last two terms will only be important in the case $f = -f'$, which will be discussed below. The integration limits arise from kinematic considerations and from taking the parton model as valid for $Q^2 > Q_0^2 \simeq 5 \text{ GeV}^2$.

At the energies of interest, the propagator damps the cross-section for high enough x , effectively limiting its value to $x \leq M_W^2/s \simeq 10^3 \text{ GeV}/E(\text{GeV})$. For energies above 10^9 GeV , we are probing values of x well below the available data. There are several approaches for extrapolating the parton distribution functions, recently reviewed in [12]. This leads to an uncertainty in the SM neutrino cross-section predictions of about a factor 2 for the highest energies. In this paper we extrapolate below $x = 10^{-6}$ as described in [12], that is, by matching

$$x\bar{q}(x, Q) = \left(\frac{x_{min}}{x}\right)^\lambda x\bar{q}(x_{min}, Q).$$

With this method we reproduce the results for the SM neutrino-nucleon cross-section as obtained in [13] within 10%. It should be noted however that the uncertainty in the extrapolations is much lower in the present case than in the SM, in light of two reasons. One is the kinematic constraint $x > m_*^2/s$, which, for example at $m_* = 1 \text{ TeV}/c^2$ and $E = 10^{12} \text{ GeV}$, leads to x well within the available region in CTEQ6. The other is the x^2 dependence of the cross-section, as opposed to the SM linear dependence, damping the low x contributions.

In the scenario $f = -f'$, the NC photon exchange diagram is also present, and

the low Q^2 nucleon-parton interactions have to be taken into account. The differential cross-section can be written in terms of the proton structure functions F_1 and F_2 , and both the elastic and the inelastic contributions were taken into account. In the elastic case, standard proton structure functions as described for example in [9] were used. In the inelastic case, the parameterisation of the structure functions described in [14] was taken.

It should however be noted that the low Q^2 region is in the present case not as relevant as in [9]. In fact, provided we are well above the kinematic limit for excited lepton production, the DIS contribution to the cross-section is largely dominant. However, these effects become relevant near threshold and have to be taken into account. With the cross-section changes corresponding to the $ep \rightarrow l^*X$ case, we were able to reproduce the results in [9].

The total production cross-section as a function of the incident neutrino energy is shown in Fig. 2(a), for both the charged and neutral current processes, with $f/\Lambda = 15 \text{ TeV}^{-1}$ and a chosen value of the excited lepton mass. The total SM νN cross-section is also shown for comparison. In Fig. 2(b), the total cross-section is shown as a function of the excited lepton mass, for $f/\Lambda = 15 \text{ TeV}^{-1}$ and a chosen value of the neutrino energy. In both figures, the elastic and low Q^2 inelastic contributions to the NC, $f = -f'$ cross-section are shown separately.

In Fig. 3, the differential cross-sections:

$$\frac{d\sigma_{\nu N}}{dy} = \int dx \frac{d^2\sigma_{\nu N}}{dx dy} \quad (5)$$

are shown as an example for fixed values of the incident neutrino energy and of the excited lepton mass and coupling parameters. The charged current cross-section is shown, together with the neutral current cross-sections for $f = f'$ and $f = -f'$. In the latter, the elastic and low Q^2 inelastic contributions are visible, in the lowest and intermediate range of $\log_{10}(y)$, respectively.

These distributions determine the fraction of the incident neutrino energy carried away by the hadronic component X and thus, to some extent, the energy of the observable extensive air shower. The observability of the excited lepton decay products will depend on the decay mode, as discussed in detail in section 3.

2.2 Decay

Excited leptons are assumed to decay promptly by radiating a γ , W^\pm or Z^0 boson. For $\Lambda = 1 \text{ TeV}$ and $E < 10^{21} \text{ eV}$, their decay length is predicted to be

less than 10^{-4} m and, in all the studied scenarios, they decay essentially at the production point. The decay branching ratios are also functions of the f and f' parameters. While at lower masses the branching ratios show an important dependence on the excited lepton mass, they are practically constant in the interesting mass range ($m_* > 200$ GeV/ c^2). For charged excited leptons, the electromagnetic radiative decay is forbidden if $f = -f'$ and the decays proceed exclusively through Z^0 and W^\pm bosons, with branching fractions of about 40% and 60%, respectively. However, as long as $f \neq -f'$, there is a significant contribution to the total decay width from the electromagnetic radiative decay, even if the difference $|f| - |f'|$ is much smaller than $|f|$. In the $f = f'$ case, the electromagnetic radiative decay is largely dominant at masses below the W^\pm , Z^0 gauge boson masses. In the presently interesting mass range, the decay into the W^\pm is again about 60%, while the branching ratios of the decays through a photon or a Z^0 are of the order of 30% and 10%, respectively.

In cosmic ray air shower experiments, only the excited lepton decay products originating hadronic or electromagnetic showers will contribute to the EAS. Thus, hadronic jets from the decay of heavy gauge bosons, electrons, and photons will contribute to the shower energy, while final state neutrinos and muons will go undetected.

High energy taus may produce double bang signatures of the type described in [15,16]. In fact, in the relevant energy range, taus have an interaction length in air which is much larger than their decay length, and a decay length large enough for the production of a well separated second bang - a second shower produced by its decay.

3 Limits and sensitivities

The expected number of observed excited lepton events is given by:

$$\mathcal{N} = N_A \int \frac{d\phi_\nu}{dE_\nu} \sigma_{\nu N} \mathcal{A} \Delta T dE_\nu, \quad (6)$$

where $d\phi_\nu/dE_\nu$ is the incident neutrino flux, $\sigma_{\nu N}$ is the neutral or charged current production cross-section, depending on whether neutral or charged excited lepton production is considered, \mathcal{A} is the acceptance of the experiment for the extensive air showers produced by these final states, ΔT is the observation time interval and N_A is Avogadro's number. It is assumed that the attenuation of neutrinos in the atmosphere can be neglected, which is a safe assumption for total neutrino-nucleon cross-sections in the range relevant for the present study. For larger values of the cross-section, the treatment discussed in [17] should be applied. The estimation of the different factors in the expression is discussed below.

In this work the Waxman-Bahcall (WB) [18] bound with no z evolution, $E_\nu^2 \frac{d\phi}{dE_\nu} = 10^{-8}$ [GeV/cm² s sr], is assumed. This flux is much lower than the cascade [19] or the Mannheim-Protheroe-Rachen upper bounds [20] and is, in the relevant neutrino energy range, higher but of the same order of magnitude of the “best prediction” computation for cosmogenic neutrinos presented in [17]. Taking into account the existence of neutrino oscillations over cosmological distances, equal flux (one third of the WB flux) for each neutrino flavour was considered.

The neutral and charged current excited lepton production cross-sections in neutrino-nucleon collision processes $\nu N \rightarrow \nu^* X$ and $\nu N \rightarrow \ell^* X$ are the ones computed in section 2.1.

The observation times were assumed to be: 10 years for Auger, 3 years and 10% duty cycle for both EUSO and OWL. For Agasa and Fly’s Eye, we followed reference [21].

3.1 Acceptance

The acceptance $\mathcal{A}(E)$ in equation 6 includes both the geometrical aperture, the target density and the detection efficiency factors:

$$\mathcal{A}(E) = \int \rho(\ell) A(E) \cos\theta \epsilon(E) \Delta\Omega d\ell,$$

where $A(E)\cos\theta$ is the effective area, $\rho(\ell)$ is the atmospheric density profile, $\epsilon(E)$ is a global detection efficiency factor and $\Delta\Omega$ is the observation solid angle. Under similar assumptions, acceptances have been computed for different experiments in the context of the estimation of the sensitivity for cosmic neutrinos [21,22,23,24]. It should be noted that, whereas these acceptances are valid for any νN interaction process, the relation between the shower energy and the primary neutrino energy is process dependent. Taking the SM as an example, whereas in the charged current process $\nu_e N \rightarrow e N$ the energy of the observed extensive air shower corresponds to the energy of the incident neutrino, this is not the case for the remaining neutrino families and for the neutral current case, $\nu N \rightarrow \nu N$, in which the final state neutrino goes undetected. The fraction of the primary energy that goes into EAS energy in the SM NC process is of the order of 20% for energies around 10^{19} eV, and decreases slowly with energy. It is thus convenient for the present purposes to plot the neutrino acceptances of the different experiments as a function of the shower energy. These acceptances are compiled in Fig. 4(a). For Auger, the most conservative estimate of the acceptance for quasi-horizontal showers as determined by Monte Carlo simulations [22] was considered. The acceptance of AGASA was conservatively taken as the acceptance for electromagnetic

showers given in [21]. A discussion of the acceptance of AGASA for hadronic and electromagnetic showers can be found in [17]. The acceptance of EUSO was taken from the estimation in [23], including the trigger and visibility of the shower maximum conditions but no cloud effect (which was included as a reduction of the duty cycle). The acceptance of OWL was estimated from the aperture given in [8] for an altitude of 500 Km.

In Fig. 4(b) the exposures of the different experiments are shown, which take into account both the acceptance and the effective observation time. The assumed observation periods are the ones described above (and quoted in the caption of the figure).

In the case of excited lepton production, $\nu N \rightarrow \nu^* X$ or $\nu N \rightarrow \ell^* X$, the relation between the shower energy and the incident neutrino energy is obtained from the $d\sigma_{\nu N}/dy$ distribution (see section 2, equation 5) and depends on the decay mode of the produced neutral or charged excited lepton. The fraction of the incident neutrino energy carried away by the hadronic component X and thus, to some extent, the energy of the observable extensive air shower, are determined by these distributions (such as the one in Fig. 3). On the other hand, the observability of the excited lepton decay products will depend on the decay mode. For this reason, average values of the acceptance were computed via Monte Carlo, in the way detailed below.

For given values of the incident neutrino energy, the excited lepton mass and the f, f' parameters, the production and decay of the excited leptons were simulated, taking into account the $d\sigma_{\nu N}/dy$ distributions and the branching ratios of the excited leptons. In this generator, the model described in section 2 for excited lepton production and decay was implemented. The decay of the heavy gauge bosons arising from the excited lepton decay, as well as the hadronisation of the final state quarks, were handled by JETSET [25]. For each set of input parameter values, one thousand events were generated for each excited lepton type. For each case, the shower energy was computed (as described in section 2.2). The ratio of the shower energy to the incident neutrino energy in the different decay modes of the excited leptons is shown for example cases in Fig. 5. The corresponding acceptances were then obtained from Fig. 4. Averaging over all the generated events, an average acceptance was determined for each set of input parameters, as a function of the incident neutrino energy. The average acceptance computed for Auger is shown in Fig. 6 as a function of the incident neutrino energy and of the excited lepton mass. It can be seen that while the kinematic limit effect is clearly visible, at higher energies the average acceptances follow relatively closely the one shown in Fig. 4. The average acceptances obtained for the different experiments are shown in Fig. 7, for $E_\nu = 10^{20}$ eV and $m_* = 1$ TeV/ c^2 . Again, the average acceptances are close to the ones shown in Fig. 4. This is due to the fact that in the dominant decay modes the fraction of the neutrino energy visible as

shower energy is relatively high.

3.2 Results

Using equation 6, the sensitivity of the different experiments to excited lepton production, as a function of the excited lepton mass, was studied. Requiring the observation of one event, the sensitivity on the ratio f/Λ (see section 2) as a function of the mass was derived.

Fig. 8 shows the obtained sensitivities for first family excited leptons (excited electrons and excited electron neutrinos) as a function of the excited lepton mass, for the scenarios $f = f'$ and $f = -f'$. The assumed observation times are the ones detailed above (and quoted in the caption of the figure). For comparison, limits on f/Λ obtained in direct and indirect searches for excited leptons at LEP are also shown [26]. LEP direct searches exclude f/Λ values down to below 1 TeV^{-1} , in a mass range that extends up to about 200 GeV. Indirect searches, only applicable for excited electrons with non-vanishing electromagnetic coupling ($f = f'$ in our case) extend the exclusion to much higher masses, although with a poorer sensitivity.

These results show that, for the foreseen acceptances, observation time intervals and fluxes, cosmic ray experiments may detect excited lepton production only for rather large values of the coupling f/Λ . In this situation, they will nevertheless greatly extend the mass region explored at accelerators.

Excited leptons of different flavours, both charged and neutral, were also studied. The obtained sensitivities are, for these cases, comparable but slightly worse, due to the lower shower energy, for the same energy of the incident neutrino. The results obtained for third family excited leptons are shown in Fig. 9.

Furthermore, for third family excited leptons, both charged and neutral, an energetic tau lepton could be produced in the decay. In this case, the double bang signature proposed in [15,16] could be searched for: the tau could travel long enough for its decay to produce a second shower, separate from the first one, but still within the field of view of the experiment. This rather distinctive new physics signature obviously requires a very large field of view, while the energy threshold for the observation of the second bang is also a critical issue. In fact, even for the experiments with the largest acceptances, only a few percent of the detected events are expected to have a visible second bang. Using the procedure detailed in [16], the sensitivity from the observation of double bang events in EUSO was estimated. This curve is also shown in Fig. 9, where we see that we loose about one order of magnitude with respect to the sensitivity of the experiment.

4 Conclusions

Excited leptons could be produced in the interaction of high energy quasi-horizontal cosmic neutrinos with the atmosphere via neutral and charged current processes, $\nu N \rightarrow \nu^* X$ and $\nu N \rightarrow \ell^* X$. The possibility of detecting excited lepton in present and future very high energy cosmic ray experiments was studied.

The model in [9] was used to compute charged and neutral current cross-sections for the very high energy range. The results were cross-checked with those given in [9] for ep collisions at much lower energies, and also with calculations of the SM νN cross-section at very high energies.

Monte Carlo methods were used to estimate the average acceptances, as a function of the neutrino energy, taking into account the computed differential cross-section and the excited lepton decay branching-ratios, as well as the neutrino acceptances of present and future very high energy cosmic ray experiments quoted in the literature [21,22].

Sensitivity curves in the coupling f/Λ as a function of the excited lepton mass were obtained for different experiments, assuming the Waxman-Bahcall bound for the neutrino flux, considering charged and neutral excited leptons of first, second and third family. The results show that cosmic ray air shower experiments may represent a window for excited lepton searches in a mass range well beyond the TeV, if the coupling f/Λ is of the order of some tens of TeV^{-1} .

However, an excited lepton signal would only correspond to an increase on the number of expected neutrino-induced horizontal showers. Although this is in itself a relevant prediction, the large uncertainties on the fluxes stress the need for complementary signatures, such as the double bang signature discussed above.

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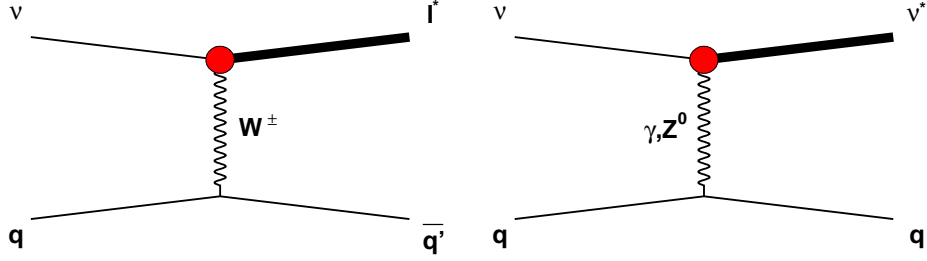


Fig. 1. Lowest order Feynman diagrams for the single production of excited leptons in neutrino-quark collisions via charged current (left) and neutral current (right) interactions. The vertex shown as a closed circle represents a ll^*V coupling ($V \equiv \gamma, W^\pm, Z^0$) proportional to $1/\Lambda$. The t-channel photon exchange can only occur in scenarios with $f \neq f'$.

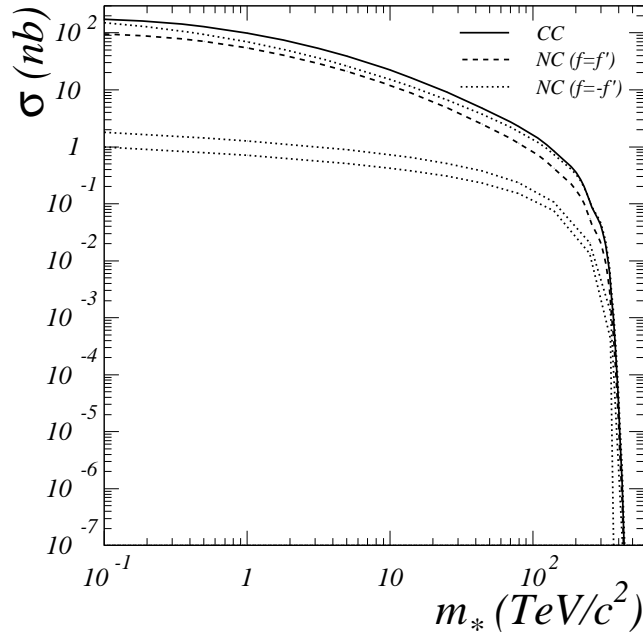
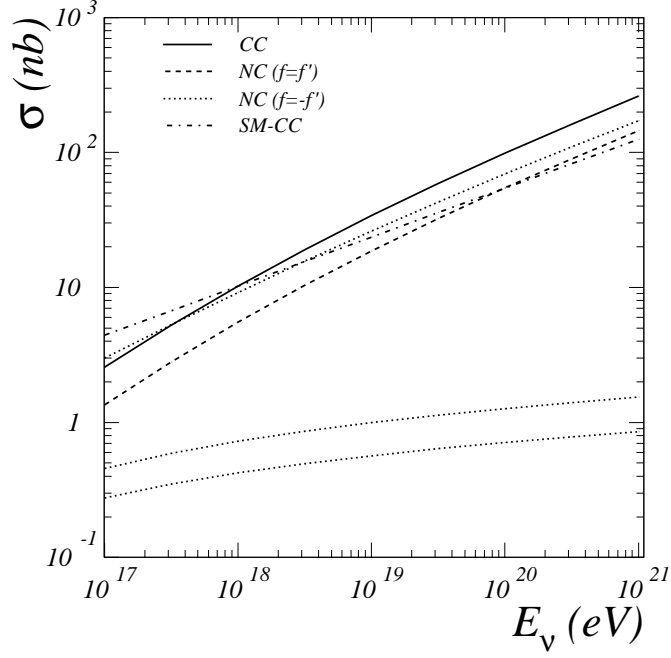


Fig. 2. Excited lepton production cross-section in νN collisions, via charged and neutral current interactions, with $f/\Lambda = 15 \text{ TeV}^{-1}$: (a) as a function of the incident neutrino energy, for $m_* = 1 \text{ TeV}/c^2$, (b) as a function of the excited lepton mass, for $E_\nu = 10^{20} \text{ eV}$. The lower dotted curves show separately the elastic and inelastic low Q^2 contributions to the NC $f = -f'$ cross-section. In (a) the SM neutrino-nucleon CC cross-section is also shown for comparison.

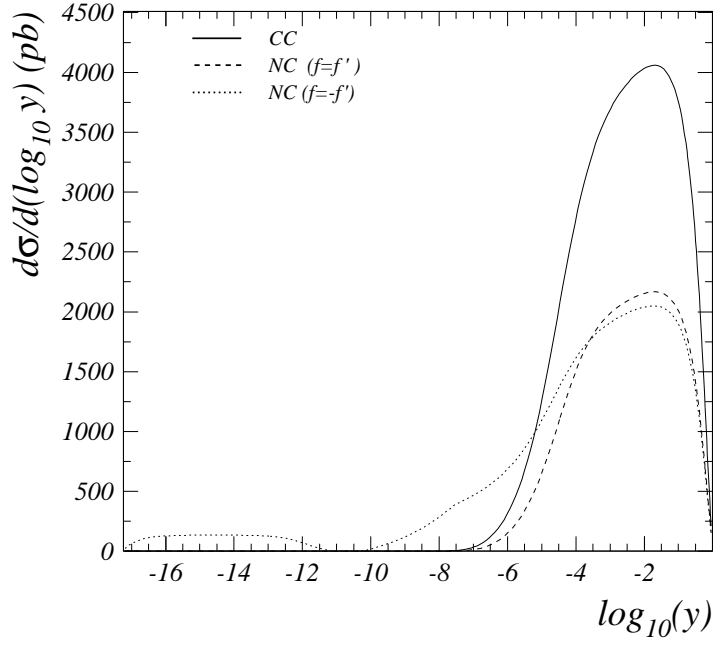


Fig. 3. Differential excited lepton production cross-section in charged and neutral current νN interactions with $f/\Lambda = 15 \text{ TeV}^{-1}$, $E_\nu = 10^{20} \text{ eV}$ and $m_* = 14 \text{ TeV}/c^2$. For NC and $f = -f'$, the elastic and low Q^2 inelastic contributions are visible, in the lowest and intermediate range of $\log_{10}(y)$, respectively.

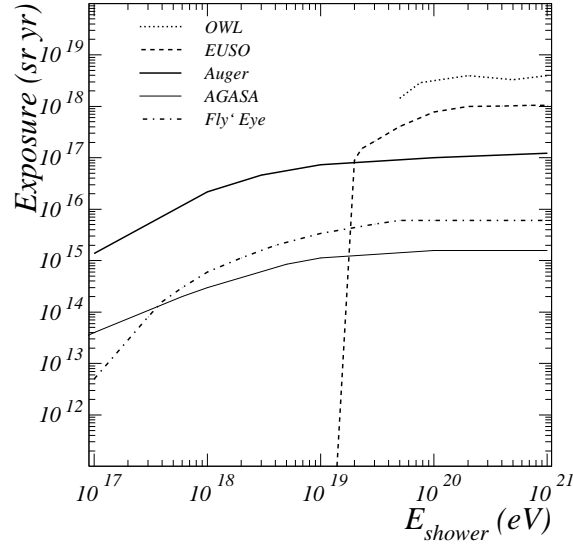
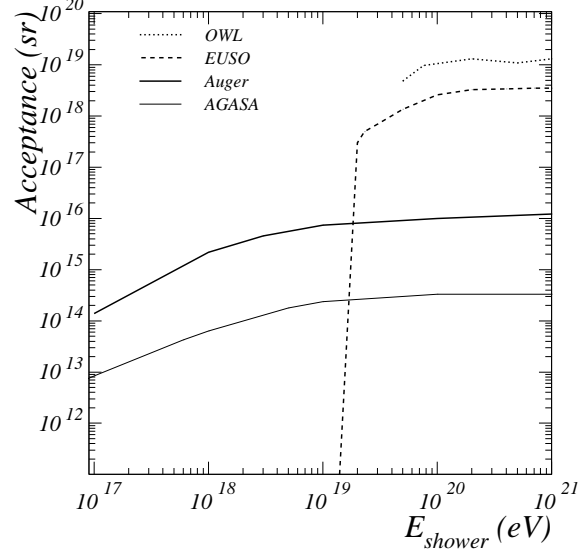


Fig. 4. (a)Acceptances and (b) Exposures of air shower cosmic ray experiments as a function of the final state extensive air shower energy. The information in references [22,21,23,24] was used. The observation times were taken as: 10 years for Auger, 3 years and 10% duty cycle for both EUSO and OWL. For Agasa and Fly's Eye, we followed reference [21]. It should be noted that the relation between the shower energy and the incident neutrino energy is process dependent.

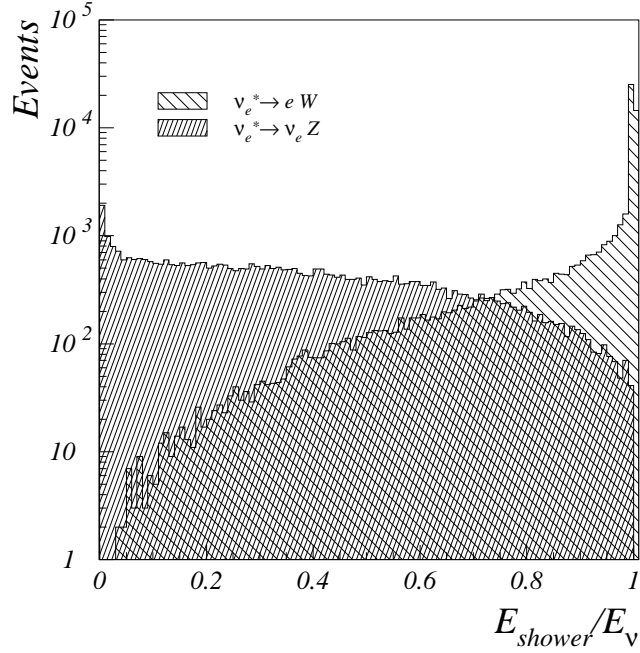
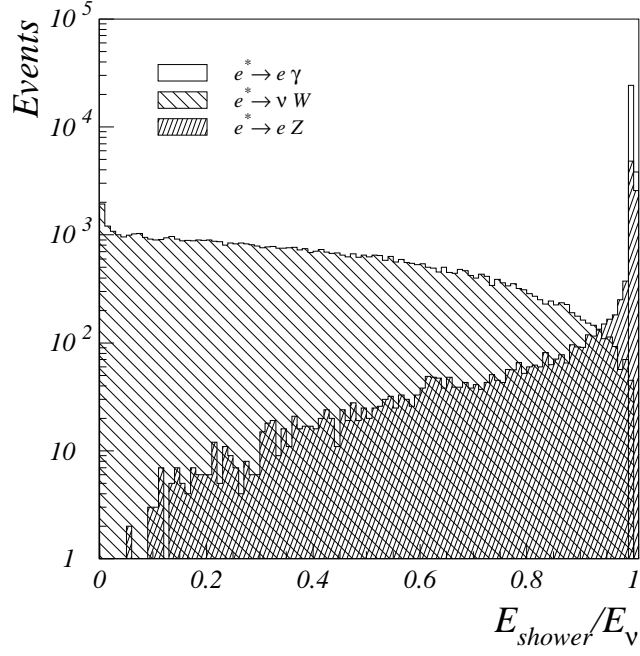


Fig. 5. Ratio of the shower energy to the incident neutrino energy in the different decay modes of the excited lepton for (a) excited electron production and (b) excited electron neutrino production, with $f = f'$, $m_* = 1 \text{ TeV}/c^2$ and $E_\nu = 10^{20} \text{ eV}$.

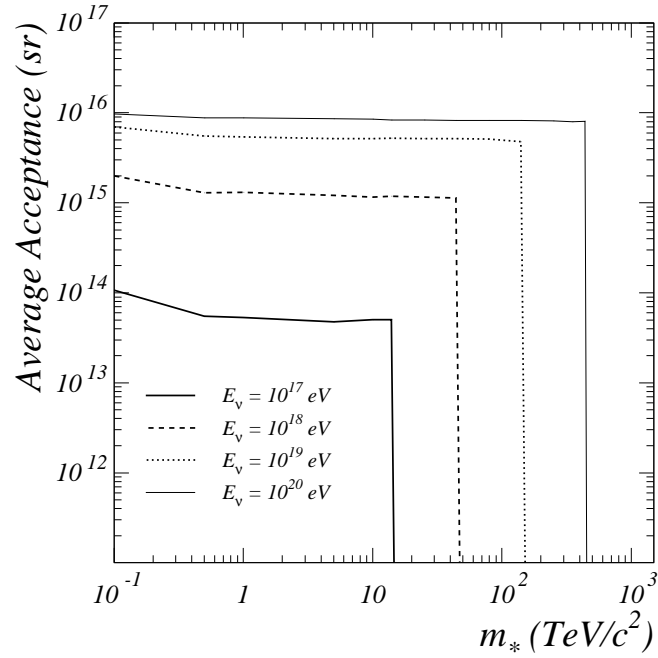
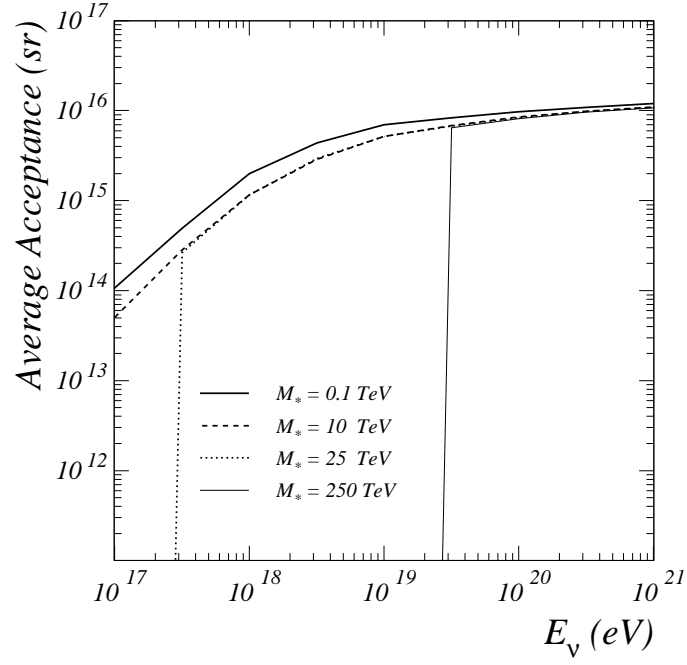


Fig. 6. Average acceptance computed for Auger: (a) as a function of the neutrino energy, for different values of the excited lepton mass; (b) as a function of the excited lepton mass, for different values of the incident neutrino energy. In this example, excited electron production with $f = f'$ was considered.

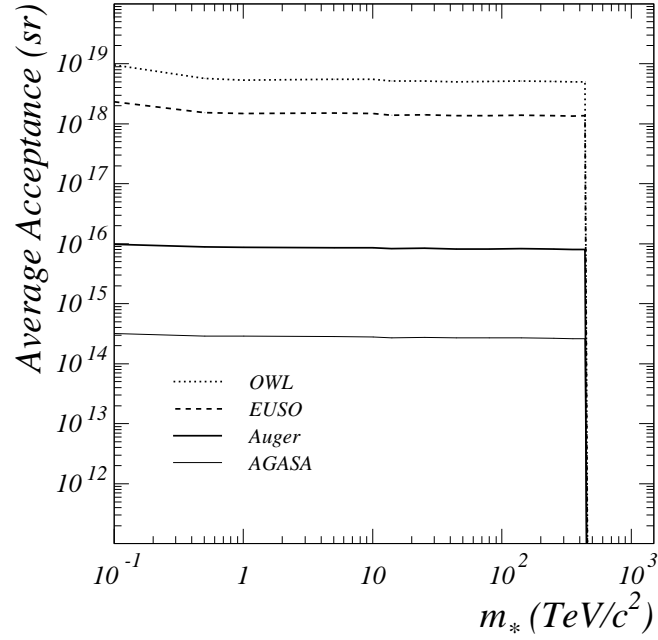
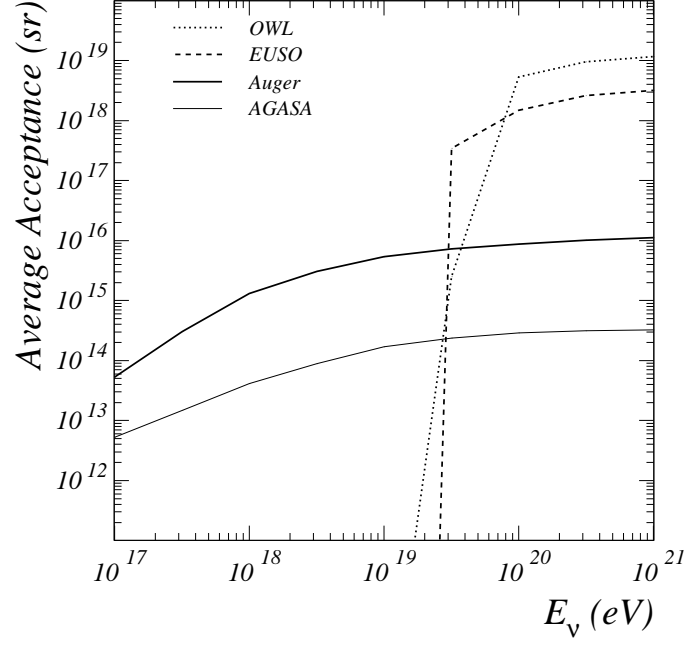


Fig. 7. Average acceptances of the different experiments as a function of (a) the incident neutrino energy, for $m_* = 1 \text{ TeV}/c^2$; (b) the excited lepton mass, with $E_\nu = 10^{20} \text{ eV}$. These results are for excited electron production with $f = f'$.

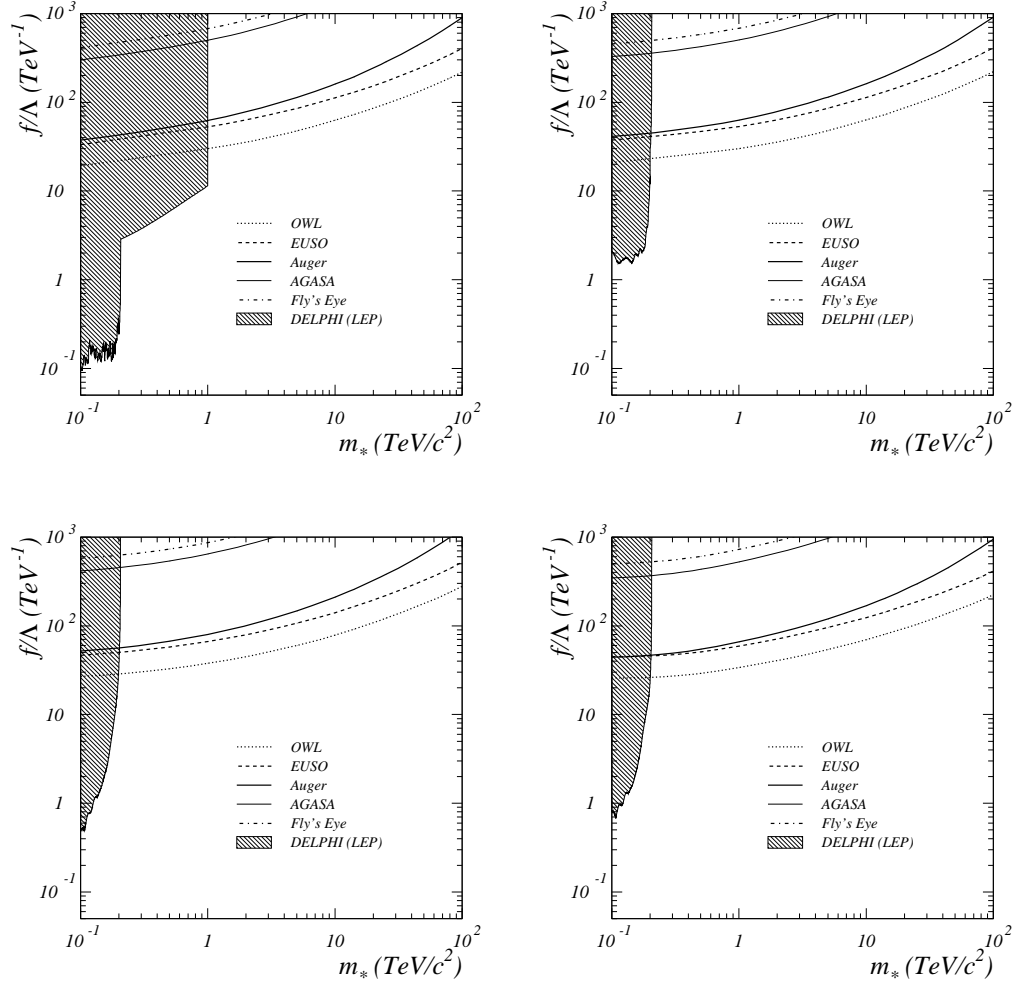


Fig. 8. Estimated sensitivities of the different experiments as a function of the excited lepton mass, for excited electrons (upper plots) and excited electron neutrinos (lower plots), in the scenarios $f = f'$ (left) and $f = -f'$ (right). The regions excluded by LEP are also shown (in dashed) for comparison. The observation times were taken as: 10 years for Auger, 3 years and 10% duty cycle for both EUSO and OWL. For Agasa and Fly's Eye, we followed reference [21].

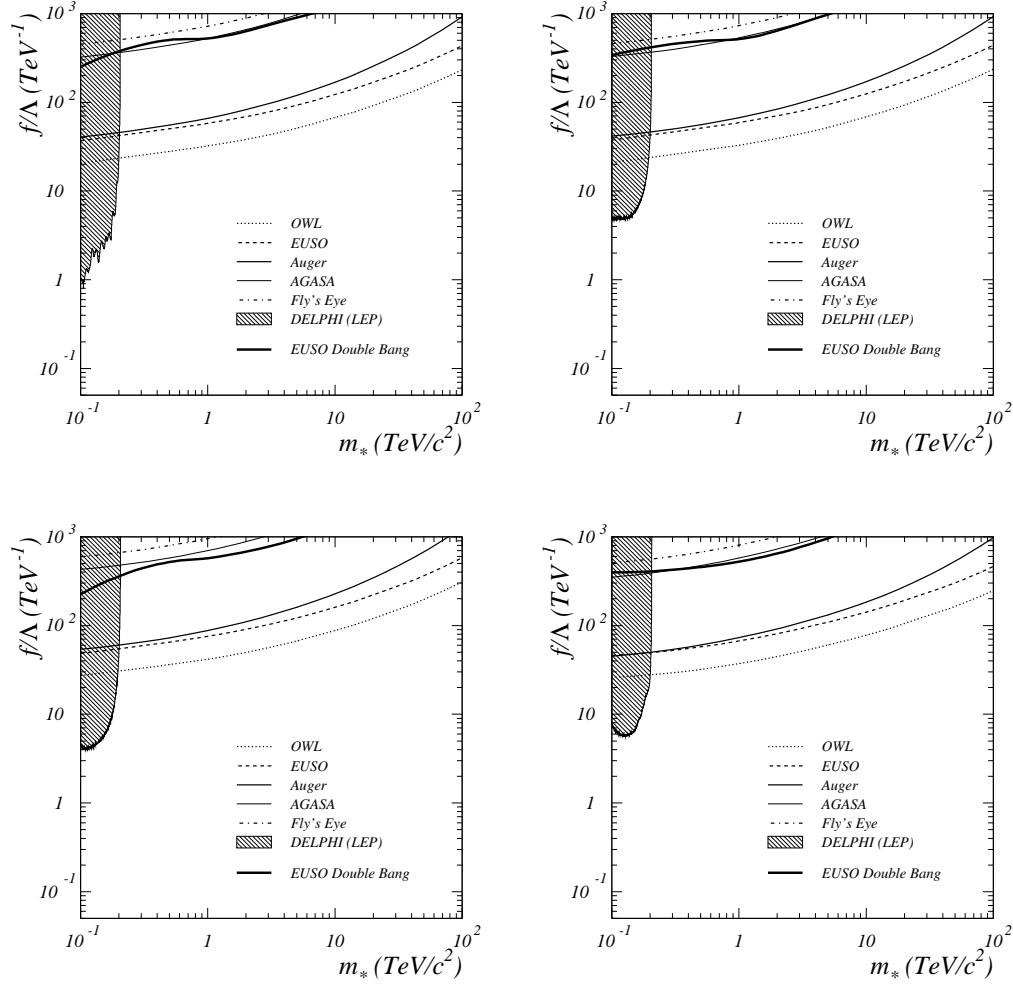


Fig. 9. Estimated sensitivities of the different experiments as a function of the excited lepton mass, for excited taus (upper plots) and excited tau neutrinos (lower plots), in the scenarios $f = f'$ (left) and $f = -f'$ (right). The regions excluded by LEP are also shown (in dashed) for comparison. The observation times were taken as: 10 years for Auger, 3 years and 10% duty cycle for both EUSO and OWL. For Agasa and Fly's Eye, we followed reference [21]. The sensitivity curves from double bang events in EUSO are also shown.